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CONTENTS

The Effect of Microporosity on the Mechanical Properties of High Strength Cast Steel Plates 1

The Solidification of Steel Castings—Part II 5

Compressed Air Pressure Risers 14

Abstracts of Fundamental Papers on Steel Casting Research . 15

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THE EFFECT OF MICROPOROSITY ON THE MECHANICAL PROPERTIES OF HIGH STRENGTH CAST STEEL PLATES

by

Foundry Section, Department of Metallurgy,
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The following represents a portion of a research project, "Investigation of Solidification of High Strength Steel Castings Under Simulated Production Conditions" completed July 1, 1959, by M.I.T. for Watertown Arsenal under Army Ordnance Contract No. DA-19-020-505-ORD-4511. The portion presented here represents the work done on one-half inch thick cast steel plates. This work dealt with the determination of mechanical properties as a function of microporosity in the plates.

Introduction

Work during the second year of research on high strength cast steel at M.I.T. dealt extensively with studies of (1) solidification variables which determine casting macrostructure, (2) susceptibility to microporosity of zones of castings with different macrostructures, (3) careful and extensive measurement of microporosity in steel castings, and (4) the effect of structure and microporosity on mechanical properties. A modified 4340 steel was used throughout the study.

The work discussed here summarizes the investigation of microporosity and mechanical properties in high strength cast steel plates. Plate castings (½ inch thick, 5 inches wide, varying lengths) were cast to study the effect of plate length and chilling on microporosity and mechanical properties of simulated production castings. It was shown that microporosity (much smaller than can be detected by ordinary inspection techniques) has an important influence on properties of these castings. Maximum properties in the plate castings were obtained in regions of minimum porosity and were 260,000 psi ultimate tensile strength with 40 percent reduction of area.

Microporosity

The usual requirement for a "sound" casting is one which is radiographically sound to 2 percent definition. Design parameters have been formulated to provide for elimination of centerline shrinkage and hence "soundness" in steel castings through proper chilling and risering. These design rules, however, do not necessarily guarantee complete absence of shrinkage on a micro-scale (i.e., microporosity or microshrinkage).

As freezing progresses in a steel casting, it sometimes becomes difficult for liquid metal to feed into the voids which form as a result of solidification contraction. These voids may exist as large cavities or as a series of smaller voids between adjacent dendrites. This finer, more randomly dispersed porosity is usually invisible to the naked eye, and must be determined by special radiographic techniques. A microradiograph showing the nature of microporosity is shown in Figure 1.

Figure 1—Microradiograph showing the interdendritic nature of microporosity (50 X, porosity is black).

Principles governing the production of castings free from microporosity are closely related to the same principles governing the production of castings free from shrinkage and porosity on a macroscale. When temperature gradients are steep, the region which consists of solid and liquid in the casting is very small. Consequently, liquid metal can be readily transported to the solid-liquid interface to fill the voids caused by solidification contraction. A second potential cause of microporosity is the precipitation of dissolved gases. The precipitation of gas will occur at the solid-liquid interface as the result of an increase in the gas content of the liquid by rejection of gas from the newly formed solid. If the temperature gradients are steep, and gas content fairly low, the gas rejected from the solid can diffuse from the solid-liquid interface into the remaining liquid, and so even when dissolved gases contribute to microporosity, good directional solidification should minimize this porosity.

The technique of microradiography used for determining microporosity consists of placing a thin sample of steel in the beam of X-rays and collection of the transmitted image on a piece of photographic film. Generally, the photographic film is placed in direct contact with the sample so that a one-to-one correspondence with the sample is obtained. Perhaps the chief drawback to the microradiographic technique is the difficulty of preparing suitable test pieces. It is necessary that the specimen be thin, of the order of 0.003 - 0.006 inch for precision work, have a good metallurgical polish on both sides, and parallel faces. The samples of this investigation were radiographed on a General Electric X-ray machine of the type normally used for diffraction studies.

The amount of microporosity was evaluated by placing a grid on the magnified radiograph and counting the number of squares in which micropores were found. The amount of microporosity was determined as:

$$\text{Percent Microporosity} = \frac{\text{number of squares containing micropores}}{\text{total number of squares}} \times 100$$

This method of rating microporosity results in a "percent microporosity" that is considerably magnified with respect to true volume percent. The magnification comes from the fact that the method, in effect, measures relative area of microporosity, but on a piece of finite thickness. The actual magnification probably depends somewhat on pore size as well as on experimental technique, but it does not appear unreasonable to expect the percent microporosity, as measured by this procedure, to be the order of 3 or 4 times the true volume percent.

Experimental Procedure

Two heats of plate castings (to be referred to here as Heat A and Heat B) were poured. Melting was carried out in a magnesia-lined induction furnace, using high purity charge material. Calcium-manganese-silicon and aluminum were used for deoxidation. The steel used conforms to the specifications for A.I.S.I. grade 4340. The chemical analyses of the two heats were:

ELEMENT (WEIGHT PERCENT)

	C	Si	Mn	Cr	Ni	Mo	S	P
Heat A	.38	.32	.72	.87	1.87	.25	.009	.007
Heat B	.40	.25	.85	.80	1.81	.26	.008	.013
Aim	.40	.30	.80	.80	1.80	.25	—	—

A series of plate castings of varying lengths were poured from each heat. The plates were one-half inch thick, five inches wide, end risered (Figure 2). Plates were cast of five, three, and one-inch lengths. In each heat, one series of plates was chilled at the end opposite the riser, whereas a comparison series was cast unchilled. The plates were all X-rayed and found to be radiographically sound to 2 percent definition. Each plate was sectioned into test bars and specimens for microradiographic examination.

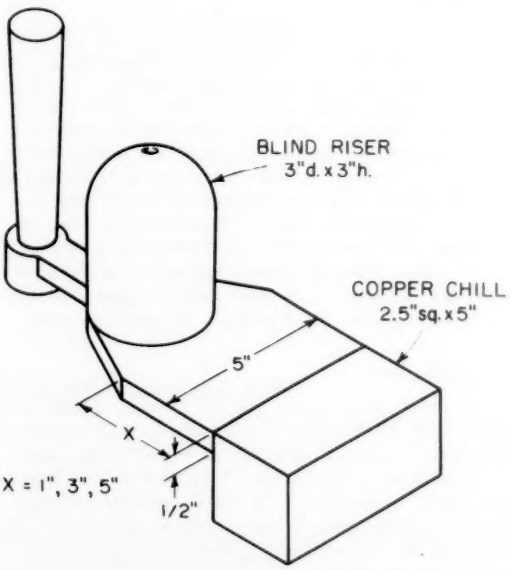


Figure 2—Plate casting design.

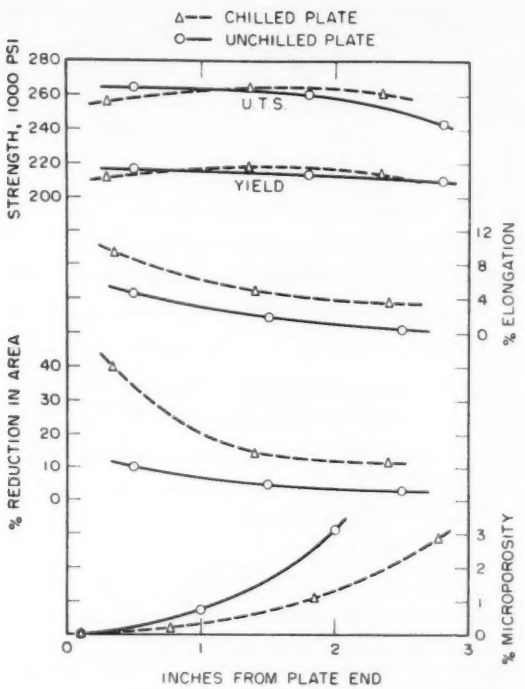


Figure 3—Summary of tensile test data for 3-inch plates, Heat A.

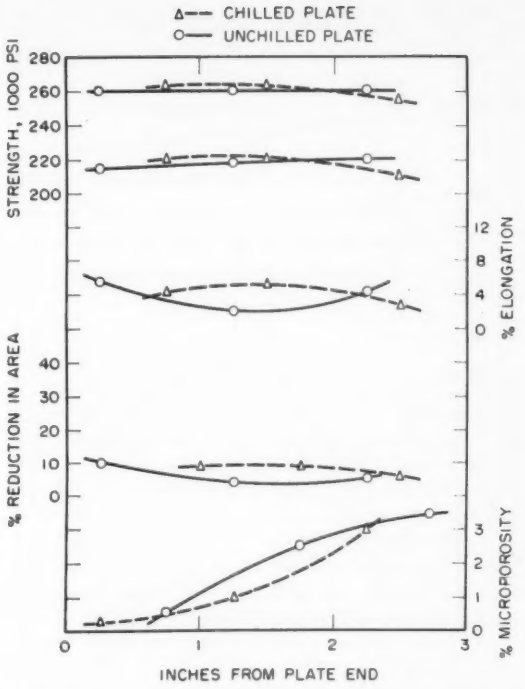


Figure 4—Summary of tensile test data for 3-inch plates, Heat B.

Test bars were given the following heat treatment:

Temp. (Degrees F)	Time (Hours)	Quench
2200	3	Air cool to R. T.
1750	3	Air cool to R. T.
1600	3	Furnace cool to 1400 ° F
1400	2	Oil quench
400	2	Water quench
400	2	Water quench

Results and Discussion

As a result of careful examination of the amount of microporosity present along the lengths of the plates (by the microradiographic technique described), and correlation of this porosity with location in the plate, the graphs of Figures 3 through 6 were prepared. These data show that a definite relationship exists between microporosity and ductility. However, tensile and yield strengths are relatively unaffected by microporosity, in the amounts studied.

Figures 3 and 4 show the relationship between mechanical properties, plate location, and microporosity for plates 3 inches long, and for two different heats. In Heat A (Figure 3) reduction in area as high as 40 percent was obtained when microporosity was essentially absent. High ductilities were not obtained in Heat B (Figure 4), probably because of the relatively high phosphorus content (.013 percent).

Mechanical property data for the 5-inch long plates are similar to those obtained for the 3-inch plates. Impact test data for the plates, somewhat surprisingly, show little correlation with microporosity. Data for the low-phosphorus heat (Heat A) are plotted in Figure 5 versus plate location.

In Figure 6, a summary is given of the percent microporosity obtained in the three and five-inch plates (chilled and unchilled). It should be borne in mind that "percent microporosity" used herein refers to percent microporosity as determined by the special microradiographic technique employed. This "percent microporosity" is a greatly magnified quantity with respect to true volume percent. Figure 6 clearly illustrates that it is extremely difficult to feed a steel casting to complete soundness, and that such soundness is obtained only very near a chill or casting edge. Amount of microporosity obtained is dependent on degree of feeding and hence on thermal gradient;

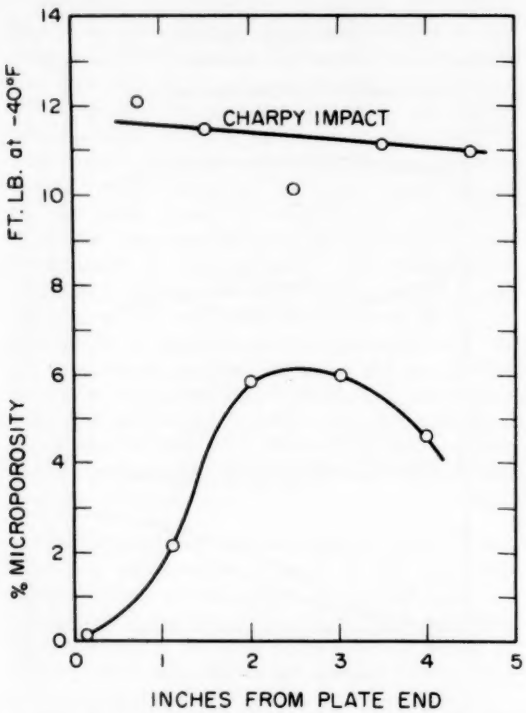


Figure 5—Summary of Charpy V-notch impact test and microporosity data, Heat A.

this microporosity therefore increases sharply with increasing distance from the plate end (or chill), and may or may not fall off slightly near a riser.

An interesting relationship between ductility, as measured by reduction of area, and microporosity is shown in Figure 7. In addition to the data accumulated from the plate castings, data from the other experimental castings of the original report are also shown on the graph. The data show conclusively that low values of microporosity are essential if high ductility values are to be obtained. It is interesting to note that seven specimens had ductilities greater than 20 percent reduction of area and that all seven had less than 0.5 percent microporosity present. It is also interesting to note that five of the seven values which were below 20 percent reduction of area (and had less than 0.5 percent microporosity) were from Heat B, which was the heat containing higher phosphorus than any other in the investigation.

Conclusions

1. A definite correlation exists between microporosity and ductility—relatively large amounts of microporosity are associated with low ductility.

2. Tensile and yield strengths are relatively unaffected by microporosity (in the amounts studied).

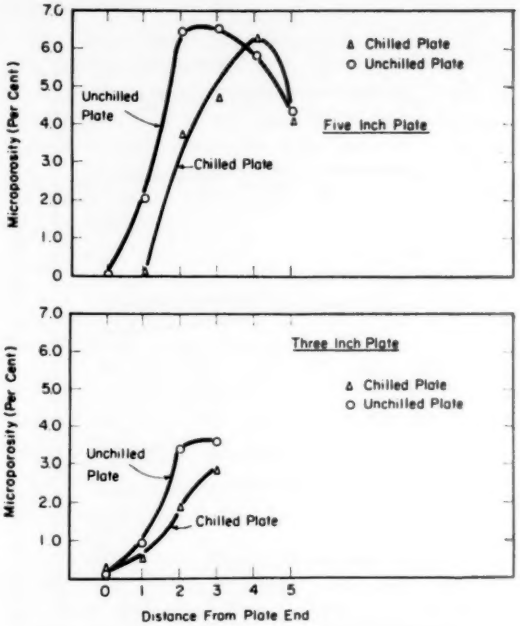


Figure 6—Microporosity survey in plate castings (each point represents an average of data from two to four different castings).

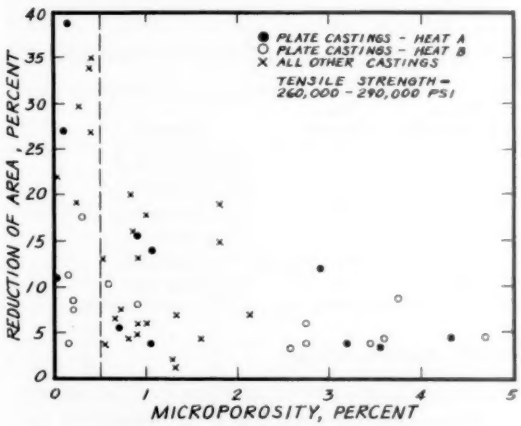


PLATE CASTINGS - HEAT A
PLATE CASTINGS - HEAT B
ALL OTHER CASTINGS
TENSILE STRENGTH = 260,000 - 290,000 PSI
REDUCTION OF AREA, PERCENT
MICROPOROSITY, PERCENT

Figure 7—Relationship of ductility to microporosity (values taken from all experimental castings).

3. Steel castings produced without extreme control of solidification possess substantial microporosity that is not detected by ordinary inspection techniques.

4. The amount of microporosity increases sharply with increasing distance from the plate end (or chill), and may or may not fall off slightly near a riser.

THE SOLIDIFICATION OF STEEL CASTINGS—PART II

by

H. G. Fraunhofer† and C. A. Rowe†

Contained herein is Part II of a comprehensive and up-to-date review of the literature on the subject of solidification of steel castings. Part I, which appeared in the preceding issue of the Journal of Steel Castings Research, discussed basic aspects of solidification and unique aspects characteristic of the mode of solidification of steel.

FACTORS AFFECTING THE SOLIDIFICATION OF STEEL

Effect of Mold Material

The mold material affects the mode of solidification of a steel casting primarily by its ability to extract heat. The greater the heat extracting ability of the mold material, the greater will be the advance of the start and end of freeze waves through the casting. A knowledge of the heat extracting ability of a molding material is essential to the practical foundryman interested in applying controlled directional solidification to produce castings free from internal cavities. A common application of this knowledge is in the use of metal chills to increase the rate of solidification at a point distant from a riser or the use of insulating sleeves around a riser to decrease the rate of solidification.

Steel Founders' Society[5,6] has investigated the chilling ability of various molding materials with the aim of finding materials which might be used as moldable chills or insulators. Cooling curves for the various materials tested are shown in Figures 12(a) and 12(b). A graphical comparison of the chilling ability of the various molding materials corrected to a standard pouring temperature of 2870 degree F is presented in Figure 13.

Effect of Metal Chills

The preceeding discussion has clearly shown that the most effective means of extracting heat from a solidifying casting is through the use of a metal chill. Previous curves (Figure 10) have shown the effect of a chill mold in the progression of start and end of freeze waves from the walls of a 7-inch block-type casting. It was shown that a steel casting in a metal mold would complete its solidification in 20 to 25 percent of the time required for the same casting in a sand mold.

†Assistants to the Technical and Research Director, Steel Founders' Society of America

Figure 14 shows the advance of the end of freeze waves in 2-inch thick plates and 4-inch thick bars in both the end-chilled and unchilled conditions. The bars were 4 x 4 inches and the plates had a width equal to 5 times their thickness. The chill is seen to have a great effect upon the end of freeze wave, especially during the early stages of solidification. In addition to aiding directional solidification, several investigations[8,9,10] have shown the use of external chills to be highly beneficial to mechanical properties.

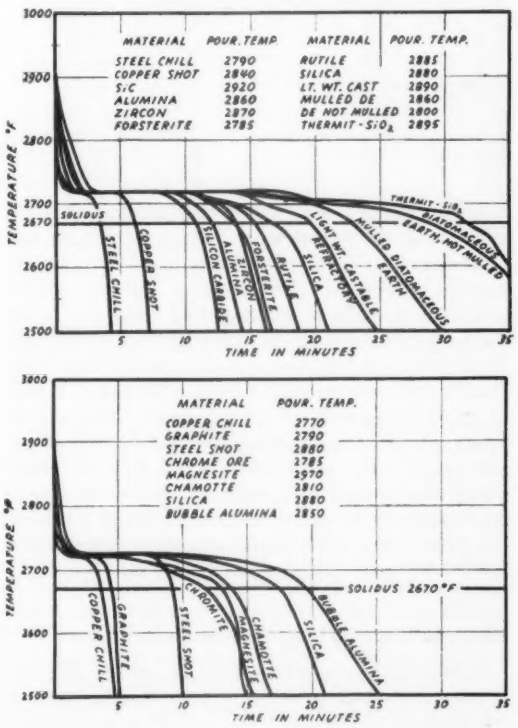


Figure 12—Cooling curves at the center of a 6-inch sphere produced in various molds. (Locke, Briggs, and Ashbrook)[6]

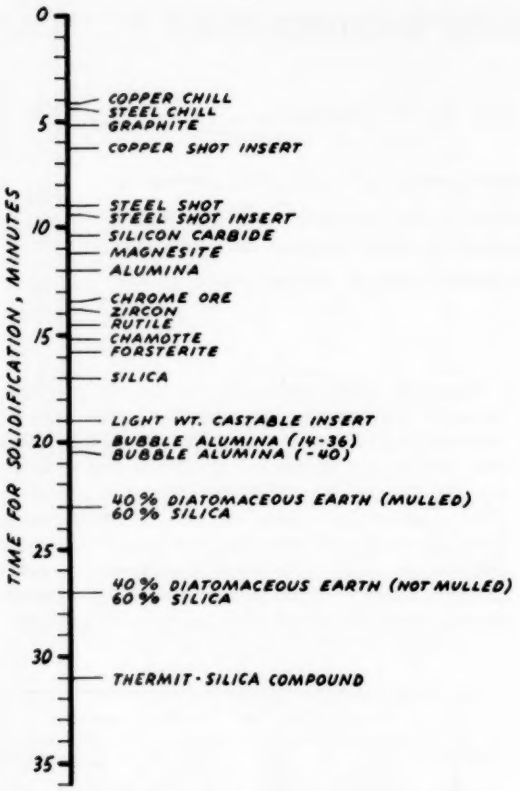


Figure 13—Effect of various molding materials on solidification time of 6-inch spheres.

Chill thickness was found to have only a slight effect upon the solidification process as may be seen in Figure 15. This figure shows that little is to be gained by going to larger chills. Studies on the thickness of chills to be employed show that chills are fully effective for a bar when the chill thickness is equal to half the thickness of the casting (½T) and that 1T chills are similarly adequate for plates. Chills of larger thicknesses are overadequate. They absorb added heat from the interface regions, but this added heat is primarily specific heat from the solid metal rather than heat of fusion. For this same reason, high-conductivity copper and water-cooled chills do not cause a measurable improvement in casting soundness over that attainable with steel or cast iron chills.

Effect of Gravity and Convection

Gravity and convection effects on the solidification of steel have been given very little consideration in the American literature. The British, however, have investigated these effects and a summary of their results[12,13,14,15] is presented.

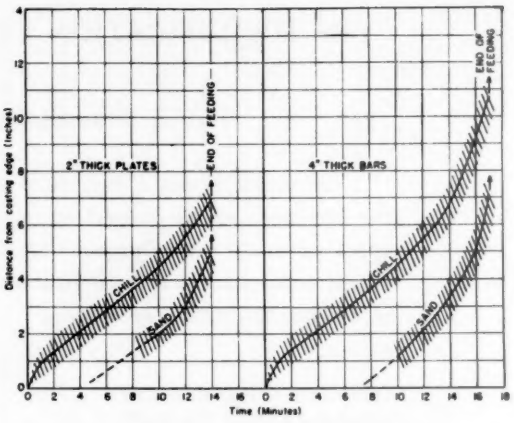


Figure 14—Progression of the end of freeze wave from the extremities of chilled and unchilled plates (left) and bars (right). (Myskowski, Bishop and Pellini)[7]

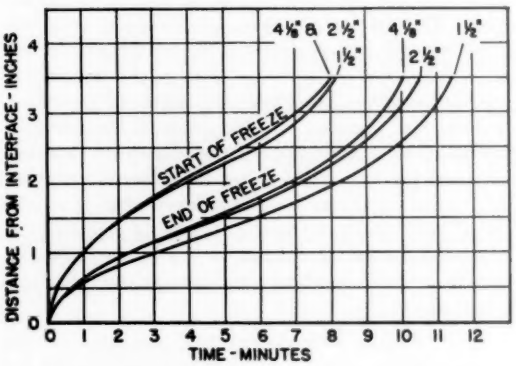


Figure 15—The effect of chill thickness in the progressive solidification of a 7 x 7-inch section steel casting. Pouring temperature 2800 degrees F; carbon content 0.60 percent; cast iron chill. (Bishop, Brandt and Pellini)[11]

Gravity and convection have their greatest effect upon the macrostructure of the casting. This effect has been explained in terms of the "falling crystallite theory". In essence, this theory states that minute embryos or crystallites form in the melt as the melt reaches the liquidus temperature, and, if conditions are right, these crystallites will fall to the lower portions of the casting. Three types of crystals are recognized: (1) columnar, which are the long thin grains, (2) equiaxial, which are grains that are not elongated in any single direction, yet show evidence of internal dendritic formation, (3) nuclear, which are very small units which have developed by growth from a very large number of nuclei, and which do not show internal dendritic formation as may be evident in the larger equiaxial crystals. Several interrelated factors come into play in determining the extent of the effect of gravity and convection upon the mode

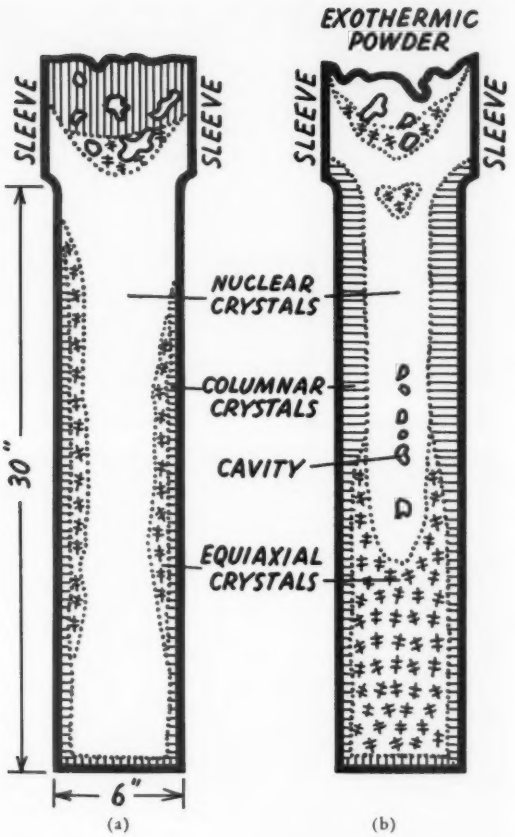


Figure 16—Schematic diagram showing macrostructures of two bar castings poured in the same mold from a common runner. 0.35 percent carbon steel; dry sand mold. (Gray)[13]

of solidification. Among these factors are superheat, chilling effect of the mold material, riser size, and thermal gradients in the casting.

The difference in the macrostructures of the two bar castings shown in Figure 16 were explained[13] in terms of the falling crystallite theory. These two castings were poured in the same mold from a common downsprue and bottom gate. They both had exothermic sleeves around the six-inch riser. The only difference was that (b) also had exothermic powder sprinkled on the riser surface in order to increase the riser life. Quite a difference is shown in the two macrostructures. Casting (a) was found to have nuclear crystals to a much greater depth than casting (b). Theoretically, solid nuclei form more readily at the top of casting (a) than casting (b). In each case, these nuclei, being more dense than the surrounding liquid, begin to fall towards the bottom of the casting. Aided by a greater thermal gradient (hence greater convection currents in the liquid) between the top and the bottom of casting (a), the nuclei are able to fall more readily and to

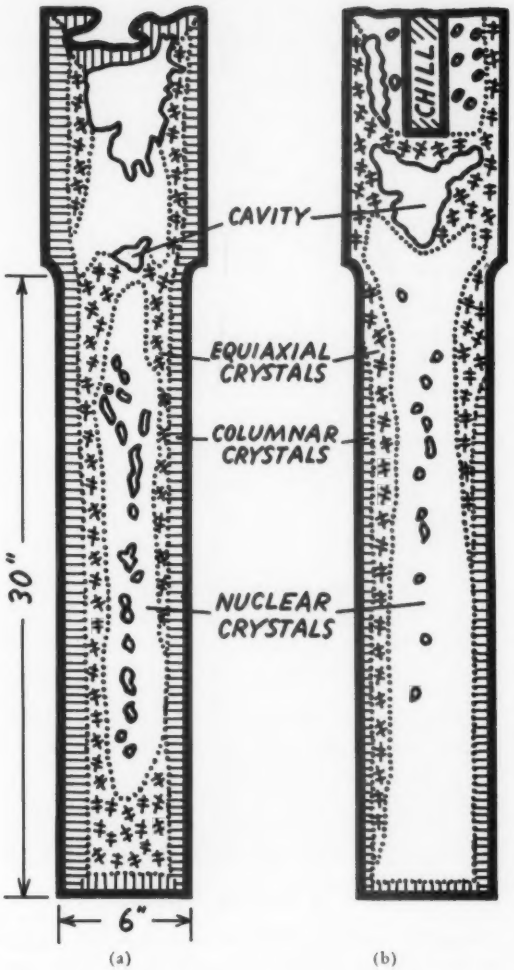


Figure 17—Schematic diagram showing macrostructures of two bar castings poured in the same mold from a common runner. 0.35 percent carbon steel; dry sand mold. (Gray)[13]

a greater depth, as shown. The difference in the macrostructures of the castings shown in Figure 17 was explained in the same manner. These bar castings are similar to those of Figure 16, except for the larger risers. These also were poured in the same mold from a common downsprue. The only difference is that the riser of casting (b) was heavily chilled by the insertion of five iron bars. Again more nuclear crystals found their way to the bottom of the casting which had the greater thermal gradient, and hence the greater convection currents, between the top and bottom.

Figure 18 shows the results of another investigation[12]. The only difference between the castings of Figure 18(a) and 18(b) was that 18(b) had a larger riser and one pound of exothermic material

was sprinkled on top. A great difference is seen in the macrostructures. Casting (a), with the greater thermal gradients between the top and bottom, is seen to be almost wholly composed of nuclear crystals while casting (b) is composed only of equiaxial and columnar grains. This same investigation showed that in a casting containing both nuclear and equiaxial or columnar grains, the portions of the casting containing the nuclear grains were purer chemically (i.e., contained less alloying elements) and possessed better tensile properties.

There appear to be some practical aspects relative to the effect of gravity and convection currents. The investigations described above show that gravity and convection effects play a part in producing a finer grained structure in the casting. It was shown that in order to induce these effects, it is necessary to have more rapid cooling at the topmost portions of the casting in order that crystallites might form early and then fall into the liquid below. This, however, is not in accord with the principles of directional solidification, which must be observed if sound castings are to be produced. Considerable success has recently been met in efforts to change the mode of crystal formation of cast steel by the use of an inoculant, i.e., a substance which, when added to the molten steel, will induce the formation of a very large number of solid nuclei. This opens the possibility of using gravity and convection effects in conjunction with an inoculant to produce a small crystal structure throughout the casting. The inoculant would necessarily be iron alloy powder or alloy carbide powder.

Solidification in a Flowing Stream

Pouring time is usually relatively short, in comparison with freezing time, and often pouring is complete before solidification begins. In such cases, casting solidification generally progresses into a nonflowing pool of liquid metal. However, in some cases, such as thin-sectioned castings, solidification begins before the mold cavity is completely filled.

Figure 19 illustrates schematically the nature of the structure obtained as steel solidifies in a flowing stream. It is of interest to note that the columnar crystals point "upstream", i.e., into the oncoming liquid. This angle of tilt is related[16] to the flow velocity of the liquid, a greater angle of tilt being associated with a greater flow velocity. In addition, the flowing stream promotes the growth of columnar crystals in preference to equiaxial grains.

An investigation of the mode of solidification in a thin section has been made[17]. The standard Taylor-Rominski-Briggs fluidity spiral was the section studied. Figure 20 illustrates a typical crystal structure observed in a 0.21 percent carbon steel at various distances from the downsprue of this casting. The investigation showed that the higher the pouring temperature, the larger the columnar crystals. The length and the angle of slope of the columnar crystals were found in all cases to decrease with increasing distance from the downsprue. Additional evidence indicated that the position at which this thin section first solidified completely was related to the pouring temperature, a high superheat promoting solidification first near the sprue and low superheat promoting solidification first at the tip.

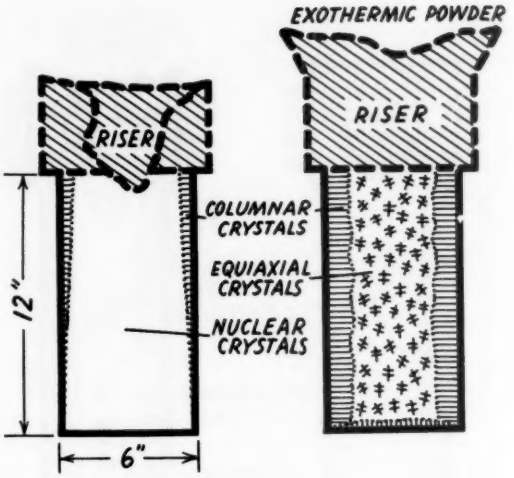


Figure 18—Schematic diagram showing macrostructures of two bar castings. Pouring temperature 2833 degrees F; 0.40 percent carbon steel. (Samways)[12]

This aspect of solidification in a flowing stream becomes increasingly important as consideration is given to thinner and thinner sections. High pouring temperatures are needed in order to run thin sections, yet these high pouring temperatures promote longer columnar crystals which converge towards the centerline to choke off the metal flow.

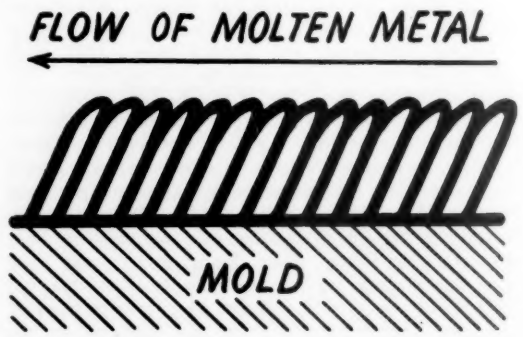
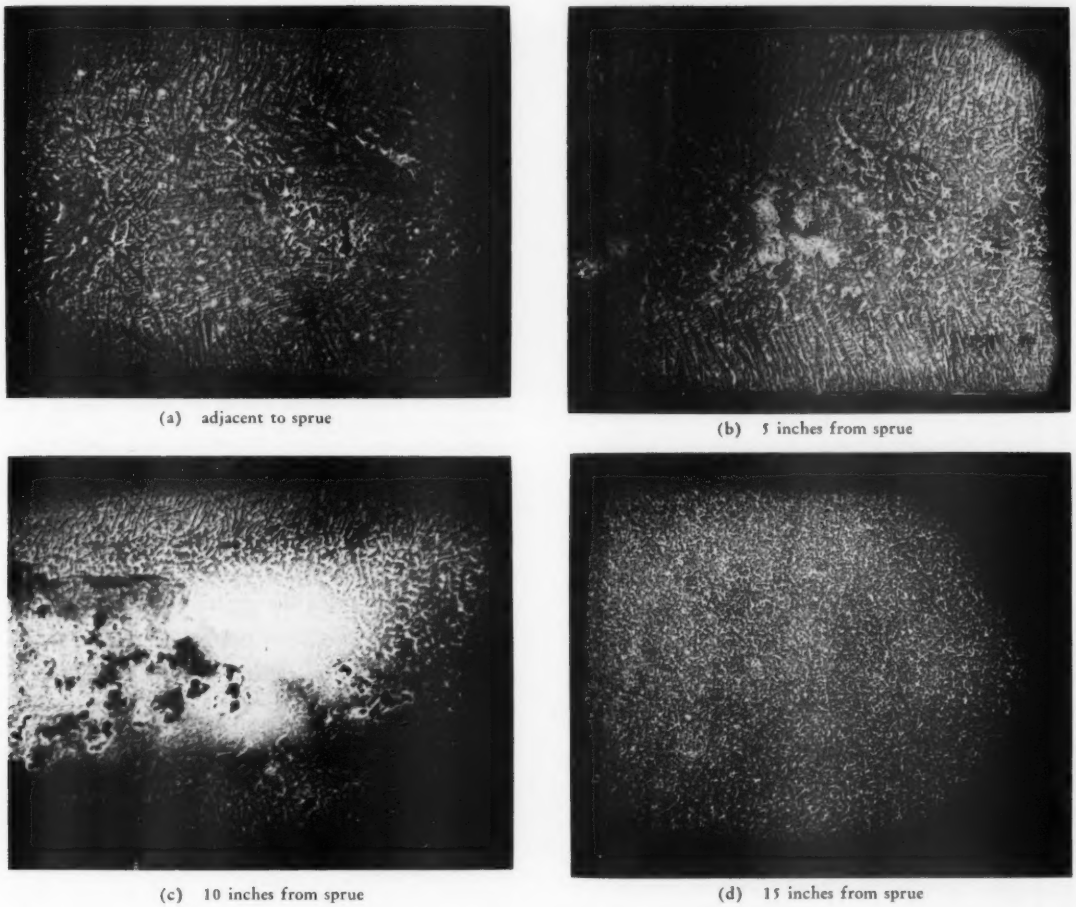


Figure 19—Schematic diagram showing the grain structure in a flowing stream.



(a) adjacent to sprue

(b) 5 inches from sprue

(c) 10 inches from sprue

(d) 15 inches from sprue

Figure 20—Grain structure observed at various positions in the standard fluidity spiral. 0.21 percent carbon steel; pouring temperature 2900 degrees F; spiral length 15 inches; spiral cut lengthwise perpendicular to parting line; magnification 8½x; reduced 25 percent in reproduction; flow from left to right. (Rowe)[17]

Other Factors Affecting the Solidification Process

Other factors, such as mold thickness, superheat, and sand moisture, also affect the mode of solidification of steel castings. These effects are summarized in Figure 21.

Figure 21(A) shows the effect of increasing the sand mold wall thickness from 2½ to 7 inches on the solidification of a 7 x 7-inch section steel casting. The effect is one of a general delay in the solidification with increasing sand thickness. The reason for the faster solidification in the case of the thinner mold walls is that the steel flask acts as a chill and becomes effective before the casting solidifies. The solidification time is increased 10 percent when the mold wall is increased from 2½ to 4⅛ inches. A further increase from a 4⅛ to a 7-inch thick mold only increases the solidification time 2 percent. It would appear from this that approximately a 4-inch mold wall is sufficient thickness for a 7 x 7-inch section. It has been reported[18] that a sufficient sand wall surrounding the casting should be 1.4T. Sand thickness greater than this does not contribute to the solidification characteristics of the casting.

Figure 21(B) illustrates the effect of pouring temperature variations on the solidification of a 7 x 7-inch section steel casting in a sand mold. A higher superheat is seen to delay the start of freezing of the steel somewhat. This delay is caused by the liberation of the additional heat resulting from pouring the higher temperature steel. Superheat also increases the solidification interval; however, the rates of travel of the various end of freeze curves are approximately the same.

Figure 21(C) shows the effect of a dry sand mold, as compared to one containing 3 percent moisture, on the progressive solidification of a 7 x 7-inch section. The presence of moisture speeds up solidification during the initial stages and causes the development of the end of freeze wave to occur earlier. This effect is apparently lost during the later stages of solidification as is indicated by the merging of the green and dry sand curves. This is additional proof of the well-known fact that steel castings in green and dry sand molds solidify in a similar manner.

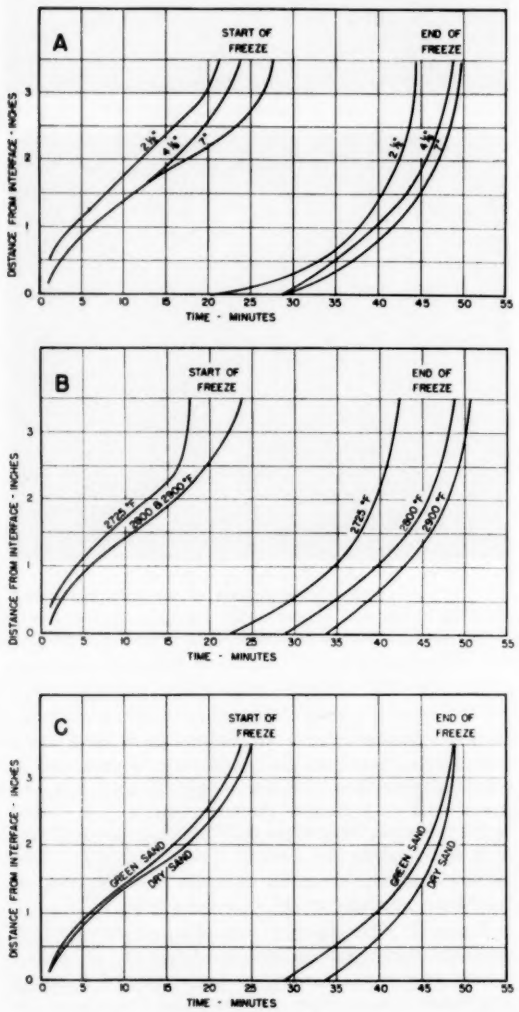


Figure 21—Progress of solidification of a 7-inch square casting. (A) green sand mold thickness series, pouring temperature 2800 degrees F; (B) green sand superheat series, mold thickness 4⅛ inches; (C) comparison between green and dry sand, mold thickness 4⅛ inches, pouring temperature 2800 degrees F. (Bishop, Brandt, and Pellini)[11]

SOLIDIFICATION TIMES FOR VARIOUS SHAPES

The rate of solidification and solidification time of steel castings are primarily determined by the thermal properties of the mold, composition of the steel, pouring temperature, section size and casting configuration. The first three variables in this list are discussed in other parts of this paper, and no further elaboration will be made on them in this section.

Solidification Calculations

The solidification of steel in metal molds has been studied theoretically, and it was determined that the rate of solidification of steel could be expressed as a parabolic function:

$$D = K\sqrt{t}$$

Here D is the thickness frozen in time t, and K is a constant of solidification.

Attempts have been made to fit this formula to experimental data on steel cast in sand molds, but it was found that the equation could be used successfully only in the early portion of the solidification of a section. The data appeared to fall on a hyperbolic rather than a parabolic curve, but a fairly good fit was obtained using the general equation

$$D = K_1 t^{0.4} + K_2 t$$

where K_1 and K_2 are constants depending upon the shape of the mold, etc.

The earliest and most well-known relationship between solidification time and casting geometry was developed by N. Chvorinov[19]. He suggested that the time required for complete solidification of a steel casting is proportional to the square of the casting volume divided by the square of the surface area of the casting, that is:

$$t_f = \frac{1}{K^2}\left(\frac{V}{SA}\right)^2 \times 60$$

where:

t_f = freezing time in minutes
V = casting volume in cubic inches
SA = casting surface area in square inches
K = constant

Application of the equation to simple shapes such as plates, bars and cylinders, must be on the basis that no (little) heat flows from the edges of plates or the ends of long bars or cylinders. A heat flow from these edges (such as exists in thick plates) will affect the volume to surface area ratio of the above equation. The volume/surface area relationships for various shapes are as follows:

Shape	V	SA	V/SA
Large Plate	LWT	2LW	T/2
Long Bar	LT^2	4LT	T/4
Cube	T^3	$6T^2$	T/6
Long Cylinder	$\pi L D^2/4$	πDL	D/4
Sphere	$\pi D^3/6$	πD^2	D/6

For spheres, cylinders and plates, K has been found to be 2.09, while for bars and rectangles it has been determined to be 1.92.

While this equation is not completely rigorous, it does represent an excellent engineering approximation. However, it should be pointed out that the relationship does not take into consideration the solidification shrinkage, and thus it cannot be applied to the dimensioning of risers.

Solidification of Simple Shapes

Most of the thermal studies on progressive solidification of cast steel have been carried out on 4 x 4, 6 x 6, 7 x 7, and 8 x 8-inch cross sections[11,20,21,22]. In such castings, progressive solidification proceeds equally from all four faces. The data obtained have been plotted in Figure 22, and a curve for square bars has been constructed.

Plates solidify progressively from only two faces. Therefore, the solidification time for a plate of the same thickness as a bar is delayed. In fact, a bar with a 4 x 4-inch cross section solidifies in 16 minutes, whereas a plate 4 inches thick requires approximately 50 minutes to solidify.

Calculations on the solidification time of cylinders and plates by the electric analogy method[23,24] are also shown as points on the graph.

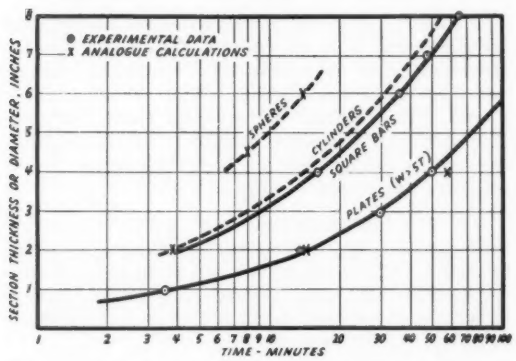


Figure 22—Solidification times for various shapes of steel castings in sand molds.

Solidification at Corner Positions

The mode of solidification is determined by heat transfer, and thus, growth of walls from which heat is being extracted at unequal rates must be considered. This is the type of freezing encountered in "L" and "T" sections. The unequal rates of heat extraction from the walls of the junction have two notable effects on solidification, i.e., the thermal center of the junction is displaced from the geometric center and the time of final solidification is changed.

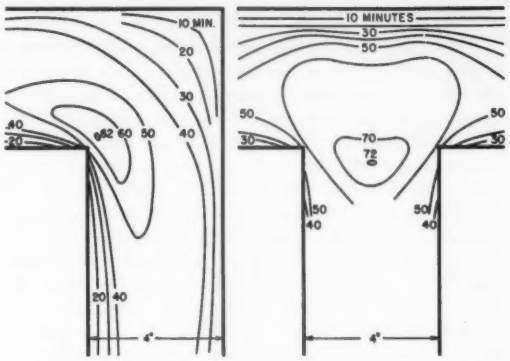


Figure 23—Progression of end of freeze wave contour in solidifying L and T sections. (Brandt, Bishop, and Pellini)[25]

A study was made of "L" and "T" junctions of 4-inch sections poured in 0.25 percent carbon steel[25]. Figure 23 shows the solidification conditions in these sections at various times during the course of freezing. It may be seen that the rate of wall build-up is most rapid at the external corner of the "L" section and slowest at the internal corner, while solidification from the flat surface of the plate progresses at an intermediate rate. The reason for this is that the heat flow paths from the external corner are divergent, and for the internal core they are convergent while they are parallel to the flat surface. As the heat flow paths move from a divergent to a convergent position, heat is conducted to a steadily decreasing mold area and the time required for final solidification increases.

It should be noted that the position of a shrinkage cavity is not the position of final solidification. Due to the effect of gravity, the last metal to solidify drains to the bottom of the hot spot region and thus the shrinkage cavity will be located directly above the last part of the section to freeze.

The previously discussed conditions have been known by the steel casting industry for some time. Thus sharp internal corners are never used but rather a radius of T/3 is used when the member section thickness (T) is greater than 3 inches. Such a radius would permit a solid skin to be formed early in the solidification cycle of the section rather than in 50 minutes as shown in Figure 23.

The relative solidification times of a 4-inch thick flat plate and 4-inch "L" and "T" sections are 48, 62 and 72 minutes, respectively. Thus it is seen that adjustment factors of 1-1/3 and 1-1/2 should be used for flat plate sections joined in "L" and "T" designs when calculating the solidification time of such sections from the volume-surface area relationships of the flat plate.

Solidification at Core Positions

The nature of solidification in bushings having a 4-inch wall thickness has been studied[25] to determine the effect of cores on freezing rate and solidification time. Castings were made using cores of 2, 4, 8 and 16-inch diameters. The results of the thermal analyses made showed that with a 2-inch core the thermal gradients over the entire section slope toward the outer surface of the casting after about 30 minutes. This indicates that at this time essentially all of the heat is flowing from the casting into the mold wall. The same conditions were found to characterize the casting with the 4-inch diameter core after 60 minutes from the time of pouring. This appears to be the borderline case in which the core stops removing heat just shortly before the end of freeze wave reaches the core surface. The 8 and 16-inch diameter cores were found to extract heat throughout the entire period of solidification. However, near the end of solidification, the gradients in the metal adjacent to the mold wall are steeper than those in the metal adjacent to the core, which indicates that a larger amount of heat is being extracted by the mold than by the core.

Figure 24 shows the progress of the end of freeze waves across the 4-inch wall section of the various test castings. Data for a 4-inch thick flat plate (representing the case of an infinitely large core diameter) and for an 8-inch diameter cylinder (representing the case of an infinitely small core diameter) are included for comparison purposes. It may be observed from the curves that as the core diameter increases, the solidification pattern moves towards the symmetrical characteristics of the flat plate, and the thermal center approaches the geometric center of the 4-inch wall. However, with a 16-inch diameter core, the thermal center is still approximately 1/2 inch from the geometric center. For the 8-inch diameter core, the thermal center is located approximately 1-1/4 inches from the geometric center, while for 4 and 2-inch diameter cores the thermal center is at the core-metal interface, i.e., the metal adjacent to the core is the last metal to solidify.

Figure 25 shows a plot of the time required for complete solidification vs. core diameter for all of

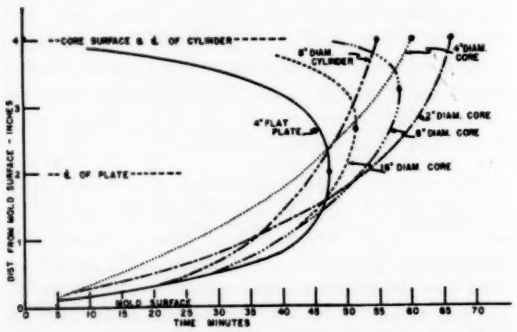


Figure 24—Progression of end of freeze waves in cored cylinder castings. (Brandt, Bishop, and Pellini)[25]

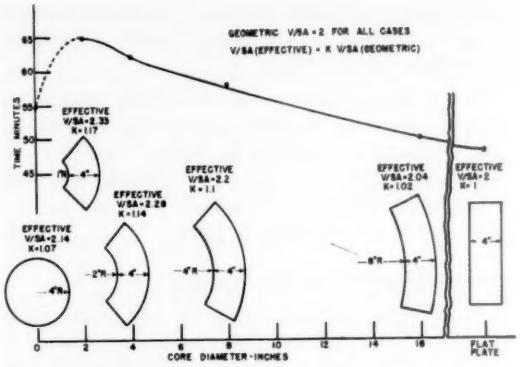


Figure 25—Relation of solidification time to core diameter. (Brandt, Bishop, and Pellini)[25]

the test castings poured. It also indicates the effective volume to surface area ratios which should be used in the calculation of freezing times for various casting configurations. However, as a practical approximation for calculation of freezing times, bushings having core diameters greater than twice the wall thickness may be considered to solidify essentially as a flat plate of equivalent wall thickness. Bushings with core diameters less than twice the wall thickness may be considered to solidify essentially as cylinders of radius equal to the wall thickness.

Summary

A knowledge of the fundamentals of solidification of steel castings is an essential foundation for the consideration of the related topics of gating, risering and directional solidification. This presentation reviews and summarizes the work of many investigators in sufficient detail to provide a sound engineering understanding of the principles involved in the solidification of steel castings.

The solidification of steel is of a progressive nature with growth toward the thermal center of a casting section. The degree to which solidification is progressive is determined by steel composition, thermal properties of the mold, temperature level of solidification, and solidification range.

The effect of various molding materials and chills is to alter the time of solidification of the casting. Gravity and convection produce finer macrostructures, whereas the flow of metal over a solidifying face produces a coarser macrostructure. Superheat and mold thickness have only a slight effect upon the mode of solidification.

The rate of solidification is shown to be slower at internal corners and core surfaces than at external corners and flat mold faces. The time required for complete solidification may be presented by the equation known as Chvorinov's rule:

$$t_f = \frac{1}{K^2}\left(\frac{V}{SA}\right)^2$$

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COMPRESSED AIR PRESSURE RISERS

by

J. Beach, W. J. Jackson and J. M. Middleton*

Description is given to some tests on rectangular shaped castings to determine whether pressure feeding with compressed air resulted in improved soundness and mechanical properties, as compared with similiar castings made with normal gravity risers.

The application of greater than atmospheric pressures to feeder heads has been described by Jazwinski and Finch,[1] who used gas producing cartridges in blind risers to force the feed metal into the casting. Later, Briggs and Taylor[2] carried out similar work, using gas producing cartridges and also applying the gas pressure from an external nitrogen cylinder. This latter investigation led to unfavorable conclusions, because no dependable improvement in feeding efficiency, as evidenced by casting quality or increased yield, was found as a result of the use of higher feeding pressures. However, Continental and Russian sources[3, 4] claim substantial progress in the technique of applying pressure to feeder heads with marked improvements both in yield and in the mechanical properties of the casting. The methods used by these workers consist in the application of compressed air through a refractory pencil positioned in the top of a blind feeder head. The compressed air is first applied when a solid skin has been formed and is then gradually built up as solidification proceeds, the final pressure being as high as 50-70 lb./sq. in. Full details of the sizes of feeder heads to be used for various section castings and times for the application and increase of pressure are given.[4]

Experimental Procedure

The method of supplying compressed air to the riser was to ram a steel tube carrying a refractory pencil into the mold, so that the refractory pencil protrudes two inches into the riser cavity. The steel tube was anchored so that it would not move during the molding operation. The refractory pencil was made of a sand, silica flour, clay and 5 percent water mix. The mix was rammed around a length of 3 mm I. D. fused silica quill and dried, the pencil core being ½ inch diameter. The use of the silica quill ensured correct positioning of the channel in the core as well as consistent dimensions. The pencil core was luted into the steel tube, using the above mix, and dried.

The sand mix used around the riser had a low permeability of 50 so that little compressed air would escape through the mold. All molds were given a coating of zircon wash and were fully dried. The compressed air attachment was connected to the compressed air line and the air pressure regulated through a gauge.

Bishop and Pellini[5] have shown that the maximum length of bar, cast either in the horizontal or vertical position, that can soundly be made from one riser is equal to $6\sqrt{t}$, where t is the thickness of the bar. It was decided, therefore, to carry out trials on simple bar shaped castings of such lengths as would be unsound according to Bishop and Pellini's formula. The castings were made in pairs, one with the pressure riser and the other with a normal open riser covered with a mildly exothermic material.

The casting dimensions are shown in Table I. The 3 x 3 x 24-inch casting solidified between 5½ to 6½ minutes, depending on various locations in the casting. The time at which air pressures were applied and the amount applied is also given in the Table. The average tensile properties are also given in Table I. These properties indicate in general that the compressed air risered castings exhibited slightly higher ductilities.

The castings were sectioned, ground and etched. All castings showed centerline segregation with microporosity.

The tests carried out show that little improvement in macro-soundness or mechanical properties resulted from the use of compressed air risers, even under the controlled conditions under which the experiments described were carried out.

A zone (a semi-infinite zone) some 6 to 7 inches in length which was uninfluenced by heat extraction from the ends of the casting, and virtually solidified by lateral heat extraction, is present in the casting. The zone solidifies almost simultaneously, hence it is difficult to see how it can be efficiently fed even if high pressures are used.

The Russian workers[4, 5] report that the application of compressed air to feeder heads considerably increased the density of the casting, and the distance that could be made sound. The castings used for this investigation were of the type which is usually unsound. Only small improvements were observed in both cases.

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TABLE I—CASTINGS STUDIED WITH AIR PRESSURE

Casting No.	Casting Dimension in.	Pressure Application, psi Time After Pouring, Min. 1	2	5	8	10	15	Tensile psi	Yield psi	Elong. %	R.A. %
								1000 psi			
1A	4 x 4 x 20	0	0	14	28	52	52	71.0	46.0	16	20.2
1B				Atmospheric				70.0	44.0	13	19.2
2A	4 x 4 x 24	0	10	15	28	52	52	68.0	45.0	13	25.2
2B				Atmospheric				62.0	45.0	10	23.0
3A	5 x 5 x 10	5	7	15	28	60	60	77.0	45.5	22.0	30.8
3B				Atmospheric				77.0	46.5	23.5	35.6
4A	3 x 3 x 24	5	10	42	42	42	42	—	—	—	—
4B				Atmospheric				—	—	—	—
5A	3 x 3 x 24	0	10	40	60	—	—	—	—	—	—

Castings 1, 2, 4 and 5 horizontally poured.
Casting 3 vertically poured.

Conclusions

The use of compressed air risers resulted in most cases in slight improvement in casting soundness and properties, as compared with similar castings fed with a normal head. The results are, however, inconsistent and not as outstanding as those reported by the Russian workers. It is doubtful whether compressed air risers would assist the foundryman in preventing macro-shrinkage, particularly as the technique requires very accurate timing and careful control if scrapped castings are to be avoided.

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ABSTRACTS OF FUNDAMENTAL PAPERS ON STEEL CASTING RESEARCH

Based on a review of the current literature on technical research subjects. (Copies of these articles available from original publishers only)

Metallography

Zaitseva, L. P., "Electrolytic Polishing of Microsections of Steel and Cast Iron in A Phosphoric-Chromic Acid Electrolyte", ZAVODSKAYA LABORATORIYA, vol. 21, 1955, #4. Henry Brutcher, Technical Translations, No. 4469, P. O. Box 157, Altadena, Calif. Price $5.75. Experimental work on the electropolishing of carbon, low alloy, high alloy steels, and white, gray, and malleable cast irons with the use of a phosphoric plus chromic acid electrolyte containing no sulfuric acid. Polishing setup and

Metallography

"New Macroetch Eases Study of High Alloy Steels", developed by Carpenter Steel Co., Reading, Pa. STEEL, October 12, 1959. A new macroetch for high alloy steels is prepared by mixing one part saturated copper sulfate solution with two parts of concentrated hydrochloric acid and heating the mixture to 160 - 170 degrees F for use. Replacing older, more hazardous strong acid mixtures, it is easy to store, does not deteriorate, is readily made up, and does not have to be prepared freshly for each use.

Metal Penetration

Vingas, G. J., "Ramming, Superheat and Alloys (Type of Metal) Effects on Metal Penetration", MODERN CASTINGS, November 1959. Metal penetration, as discussed here, is that penetration into small masses of sand surrounded by relatively large masses of metal. The major and minor variables which influence this penetration are given. This report is a continuation of work done previously with metals other than iron and steel.

Sand and Mold Research

Whitmore, D. H., and Ingerson, Q. F., "Apparent Thermal Conductivity of Molding Sand at Elevated Temperatures", MODERN CASTINGS, February 1960. Employing a general model for a porous semi-transparent insulating material, calculated values of the apparent thermal conductivity of a synthetic silica molding sand are presented which agree favorably with direct experimental observations.

Sand and Mold Research

Sarkar, A. D., "Comparison of Temperature/Time Curves of CO_2 and Green-Sand Molds", THE BRITISH FOUNDRYMAN, October 1959. A thermal arrest was observed in the temperature/time curves at 100 degrees C. The green sand mold (6% moisture) showed a much longer arrest than the CO_2 mold (0.6% moisture). Beyond the arrest period the temperature/time curves for CO_2 molds remain above those of the green sand molds on the temperature scale.

Corrosion Research

Shishmareva, L. A., "Phosphating of Iron and Steel Articles", STANKI I. INSTRUMENT, Oct. 1958, #10. Henry Brutcher, Technical Translations, No. 4641, P. O. Box 157, Altadena, Calif. Price $3.80. Data on industrially used phosphate coatings intended to provide anchorage for paint films. Two bath compositions for hot phosphating, one of them also suitable for spray coating. Two cold phosphating baths: compositions, etc. Recommended test for porosity.

Gating and Risering

"Flow of Metal into Moulds", THE BRITISH FOUNDRYMAN, January 1960. This paper shows various slides taken from motion pictures of the flow of steel in molds. The pictures primarily demonstrate what occurs in a mold when different types of ingate are used.

Heat Treatment

"You Get More Working Strength", BUSINESS WEEK, January 16, 1960. A new "thermomagnadynamics" method for refining and aligning the grain structure of metals is introduced. This results in increased strength and hardness without loss of ductility or toughness. The process is patented and may be licensed out in the near future.

Non-Destructive Testing

Clark, P. W., and Houseman, D. H., "Radioactive Tracer Investigation of Inclusions in Alloy-Steel Castings", THE BRITISH FOUNDRYMAN, October 1959. A radioactive tracer method has been used to study the role of zircon mold materials in producing inclusions in alloy-steel castings. Under the conditions of this trial it has been shown that the amount of zircon present in the interior of the finished casting is negligible.

Solidification

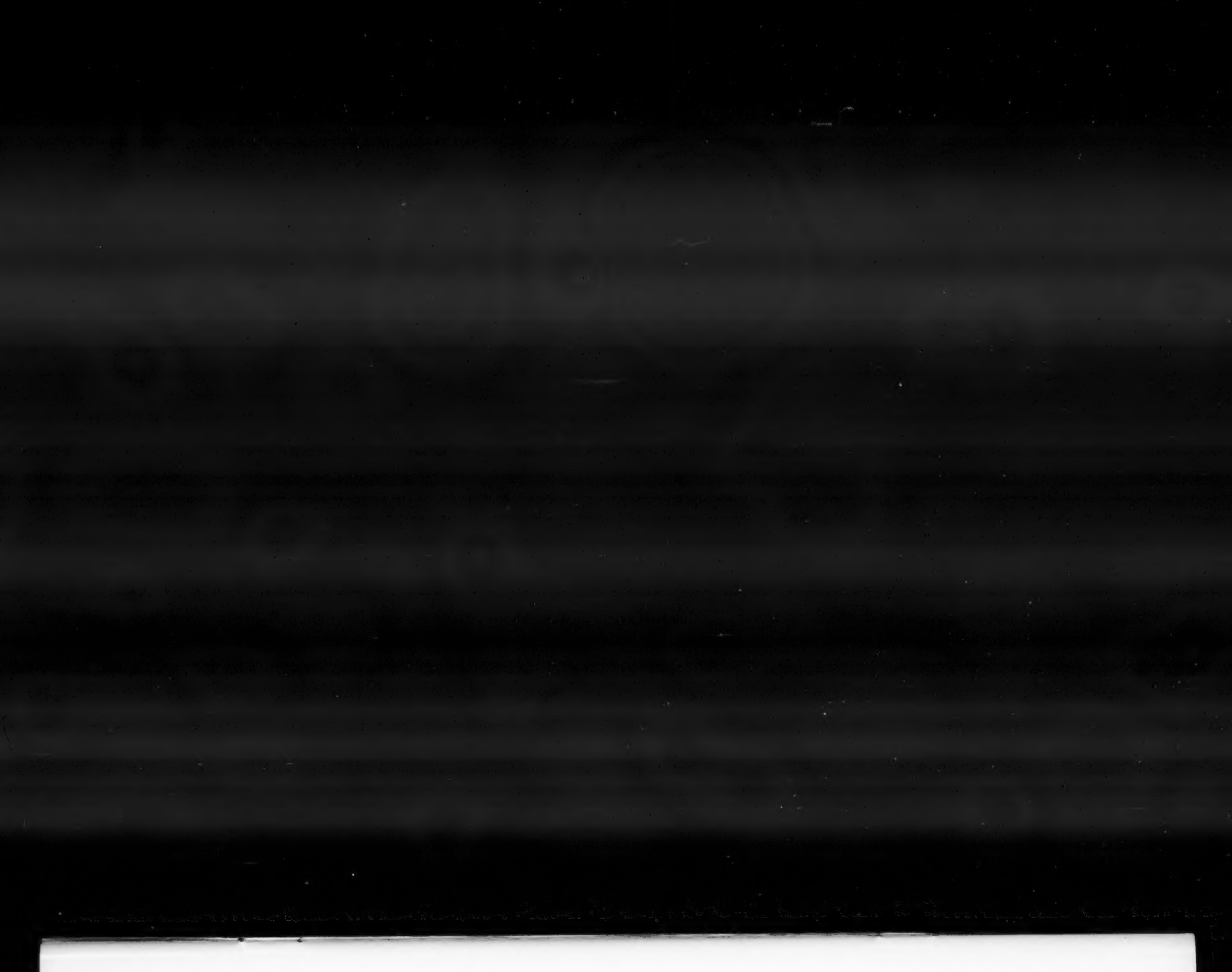
Moldavskii, O. D., and Pronov, A. P., "Effect of Aluminum, Silicon, and Chromium on Primary Structure of Low-Carbon Steel", IZV. AKAD. NAUK SSSR, OTN, Met. i Topl., 1959, #2, Henry Brutcher, Technical Translations, No. 4738, P. O. Box 157, Altadena, Cal. Price $2.90. Danilov's equation expressing the probability of nucleation in solidification of a supercooled liquid; predictions as to effect of alloying elements on primary structure of steel, made on basis of this equation.

Solidification

Bryukhanov, A., "Solidification of Steel in a Rotating Magnetic Field", STAHL UND EISEN, vol. 54, 1934. Henry Brutcher, Technical Translations, No. 566, P. O. Box 157, Altadena, Calif. Price $1.20. Principal results obtained in experiments on the casting of nonferrous metals (zinc, aluminum, aluminum bronze) in a magnetic rotating field. Description of experiments on steel (0.6% C, 3% Ni, and 0.2%, 25% Ni steels). Experimental arrangement and procedure. Results: Effect of agitation of molten steel, induced by a magnetic rotating field, on distribution of phosphorous and sulfur, crystalline structure, grain size and piping.

Properties

Hahn, G. T., Owen, W. S., Averbach, B. L., and Cohen, M., "Micromechanism of Brittle Fracture in a Low-Carbon Steel", WELDING RESEARCH SUPPLEMENT, September 1959. Tensile data, elastic limit measurements, and metallographic observations of slip, twinning and microcracks, for samples tested in the range room temperature to –250 degrees C, as well as standard Charpy data, are presented for a low carbon steel in a coarse (ASTM GS No. 4) and a fine-grained (ASTM GS No. 7) condition.

Welding

Berry, J. T., and Allan, R. C., "A Study of Cracking in Low-Alloy Steel Welded Joints", WELDING RESEARCH SUPPLEMENT, March 1960. Literature review and some preliminary results of a long-term investigation into the roles of hydrogen and the other metallurgical factors involved in the cracking of welded joints are discussed.